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Chemically stable solid lithium ion conductor

10/591714
IAP9 Rec'd PCT/PTO 06 SEP 2006

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Description

The present invention concerns chemically stable solid ion conductors in particular lithium ion conductors, processes for their production and their use in batteries, accumulators and electrochromic devices.

Mobile energy stores with high energy densities (and high power densities) are required for numerous technical devices, above all for mobile telephones and portable computers (e.g. notebooks). In this connection rechargeable chemical energy stores, especially secondary batteries and super-capacitors are of supreme importance.

The previous highest energy densities in the range of 0.2 to 0.4 Wh/cm^3 are nowadays commercially achieved with so-called lithium ion batteries. These usually consist of a liquid organic solvent (e.g. EC/DEC) containing a lithium salt (e.g. $LiPF_6$), an anode made of graphite with intercalated lithium and a cathode made of lithium cobalt oxide where the cobalt may be partially or completely replaced by nickel or manganese.

It is generally known that the service life of such lithium ion batteries is quite limited and hence they often have to be replaced even during the lifetime of the device to be supplied. Moreover, it is generally expensive to get replacements and disposal of the old batteries is problematic since some of the ingredients are not environmentally friendly.

In operation the batteries of the prior art prove to be not sufficiently powerful for many applications (e.g. offline operation of a notebook for a maximum of a few hours). The batteries are chemically unstable when electrodes are used that enable higher voltages of for example 5 V or more; the organic electrolyte components start to decompose at voltages above 2.5 V. The liquid electrolyte is in any case a safety hazard: in addition to the risk of leakage, fire and explosion, the growth of dendrites is also possible which can result in a high self-discharge and heating.

Liquid electrolyte batteries are basically unsuitable for some technical objectives because they must always have a minimum thickness and thus can only be used to a limited extent as thin energy stores e.g. on chip cards.

Solid lithium ion conductors such as $Li_{2,9}PO_{3,3}N_{0,46}$ ($Li_{3-x}PO_{4-y}N_y$, LIPON) are also known and have been used on a laboratory scale in thin layer batteries. However, these materials generally have a considerably lower lithium conductivity than liquid electrolytes. Solid lithium ion conductors having the best ion conductivities are Li_3N and Li-β-alumina. Both compounds are very sensitive towards water (moisture). Li_3N already decomposes at a voltage of 0.445 V at room temperature; Li-β-alumina is chemically unstable.

Lithium ion conductors having a garnet-like structure were presented in the paper "Novel fast lithium ion conduction in garnet-type $Li_5La_3M_2O_{12}$ (M = Nb, Ta)" by Thangadurai et al. (J. Am. Ceram. Soc. 86, 437 – 440, 2003).

Garnets are orthosilicates of the general composition $A_3B_2(SiO_4)_3$ in which A and B represent eight-coordinate or six-coordinate cation positions. The individual SiO_4 tetrahedrons are connected together by ionic bonds with the interstitial B cations.

The compounds of the formula $Li_5La_3M_2O_{12}$ (M = Nb, Ta) have a garnet-like structure. They crystallize in a cubic symmetry with the lattice constant a = 12.797 Å or 12.804 Å respectively for the corresponding compound in which M = Nb or Ta. Compared with the ideal garnet structure there is an excess of 16 lithium ions per formula unit. The La^{3+} and M^{5+} ions occupy the eight-coordinate or six-coordinate positions whereas lithium ions occupy positions having a six-fold coordination. The similarity between the ideal garnet structure and $Li_5La_3M_2O_{12}$ is due to the fact that alkaline / rare earth metal ions occupy the dodecahedral (eight-) coordinate positions and M atoms occupy the six-coordinate positions. The main difference in the structures is due to the fact that Si occupies the position with the four-fold oxygen coordination in the ideal garnet structure whereas in the garnet-like $Li_5La_3M_2O_{12}$ Li occupies the highly distorted octahedrical positions. The garnet-like structure has two types of LiO_6 octahedra; of these $Li(I)O_6$ is more distorted than $Li(II)O_6$. MO_6 octahedra are surrounded in a cubical manner by six LiO_6 octahedra and two vacant lithium positions. The vacant positions are arranged along the axes between the neighbouring MO_6 octahedra.

The garnet-like $Li_5La_3M_2O_{12}$ compounds have a significant lithium ion conductivity. In particular it was demonstrated on the tantalum-containing compound $Li_5La_3Ta_2O_{12}$ that volume conductivity and grain-boundary conductivity in the garnet-like structure tend to be of a comparable order of magnitude. Hence the total conductivity is extremely high and even above that of Li-β-alumina or of Li_9AlSiO_8 but still considerably below the conductivities of LISICON or Li_3N.

The object of the present invention was to provide improved solid ion conductors having a high ion conductivity, a low electronic conductivity and a high chemical stability. In particular the object of the invention was to provide improved lithium ion conductors.

It was found that materials having a garnet-like structure have an extremely high ionic conductivity. The novel solid ion conductors are formally derived from the already known garnet-like structures of the composition $Li_5La_3M_2O_{12}$. Surprisingly garnet-like structures having a considerably improved ion conductivity are produced from this compound by aliovalent substitution.

Aliovalent substitution is understood as the substitution of an ion by an ion of another oxidation state and the resulting charge compensation that is required can be achieved by cation vacancies, anion vacancies, interstitial cations and/or interstitial anions.

Starting with the known garnet-like structures $Li_5La_3M_2O_{12}$ the connectivity of the network can be increased and the number of available vacant positions can be varied according to the invention by aliovalent substitutions. In this connection the La^{3+} positions are preferably aliovalently substituted for example by divalent cations. The charge compensation can preferably be by means of Li^+ cations. The conductivity of the structure can be made-to-measure by suitable doping.

Furthermore any other elements or combinations of elements can be used according to the invention instead of Li, La, M and O. It is possible to obtain any ion conductors by partial or complete formal substitution of the Li cations by other metal cations and in particular by alkali ions. The solid ion conductors according to the invention are characterized by the garnet-like structure that is described in detail above.

Hence the present invention provides a solid ion conductor having a garnet-like crystal structure which has the stoichiometric composition

$$L_{5+x}A_yG_zM_2O_{12}$$

wherein

L is in each case independently an arbitrary preferably monovalent cation,

A is in each case independently a monovalent, divalent, trivalent or tetravalent cation,

G is in each case independently a monovalent, divalent, trivalent or tetravalent cation

M is in each case independently a trivalent, tetravalent or pentavalent cation,

$0 < x \leq 3$, $0 \leq y \leq 3$, $0 \leq z \leq 3$ and

wherein O can be partially or completely replaced by divalent and/or trivalent anions such as e.g. N^{3-}.

Within a structure of this formal composition L, A, G and M can each be the same or different.

L is particularly preferably an alkali metal ion for example Li^+, Na^+ or K^+. In this connection combinations of different alkali metal ions for L are also especially possible.

A represents an arbitrary monovalent, divalent, trivalent or tetravalent cation or any combinations thereof. Divalent metal cations can be preferably used for A. Alkaline earth metal cations such as Ca, Sr, Ba and/or Mg as well as divalent transition metal cations such as e.g. Zn are particularly preferred.

G represents an arbitrary divalent, trivalent, tetravalent or pentavalent cation or any combinations thereof. Trivalent metal cations can be preferably used for G. G is particularly preferably La.

M represents an arbitrary divalent, trivalent, tetravalent or pentavalent cation or any combinations thereof. Pentavalent cations can be preferably used for M. M is also preferably a transition metal, which is preferably selected from Nb and Ta. Other examples of suitable pentavalent cations are Sb and V. When selecting M it is

advantageous to select transition metal ions which have a high stability towards reduction. M is most preferably Ta.

In a structure of the above composition O^{2-} can be completely or partially replaced by other anions. For example it is advantageous to completely or partially replace O^{2-} by other divalent anions. In addition O^{2-} can also be aliovalently substituted by trivalent anions with a corresponding charge compensation.

Furthermore in the above composition
$0 < x \leq 3$, preferably $0 < x \leq 2$ and particularly preferably $0 < x \leq 1$;
$0 \leq y \leq 3$, and $0 \leq z \leq 3$. The stoichiometric ratio of the components is selected in such a manner that an overall uncharged garnet-like structure is present.

In a preferred embodiment of the present invention L is a monovalent cation, A is a divalent cation, G is a trivalent cation and M is a pentavalent cation. Furthermore in this preferred embodiment the stoichiometry of the compound is preferably:

$$L_{5+x}A_xG_{3-x}M_2O_{12}$$

wherein x is defined as above and preferably $0 < x \leq 1$.

A specialized aspect of the present invention provides a solid lithium ion conductor of the stoichiometric composition $Li_6ALa_2M_2O_{12}$ in which A denotes a divalent metal and M denotes a pentavalent metal. Within a structure of this formal composition A and M can in each case be the same or different.

A is preferably selected from alkaline earth metals, preferably from Ca, Sr, Ba and/or Mg. A can also be preferably selected from divalent transition metals such as for example A = Zn. A is most preferably Sr or Ba.

M can be any pentavalent cation for example a metal in the oxidation state +V, M is preferably a transition metal that is preferably selected from Nb and Ta. Other examples of suitable pentavalent cations are Sb and V. When selecting M it is advantageous to select transition metal ions which have a high stability towards a reduction by elemental lithium. M is most preferably Ta.

Lithium ion conductors of the composition $Li_6ALa_2M_2O_{12}$ have a garnet-like crystal structure. Compared to the known compounds of the composition $Li_5La_3M_2O_{12}$, La was formally replaced by a divalent ion A and a lithium cation and thus the proportion of lithium in the structure was increased. As a result it is possible to use the compounds of the present invention to provide considerably improved lithium ion conductors.

Compared to the compounds of the prior art, the materials of the composition $Li_6ALa_2M_2O_{12}$ have an increased lithium conductivity. For example the lithium conductivity of $Li_6ALa_2Ta_2O_{12}$ (A = Sr, Ba) of 10^{-5} S/cm at 20°C is an order of magnitude higher than that of LIPON. Due to the garnet structure of the compounds of the present invention which is a 3D-isotropic structure, the lithium ion conduction is possible in 3 dimensions without a preferred direction.

In contrast the electronic conductivity of the compounds of the present invention is negligibly small. Polycrystalline samples of the compounds of the present invention exhibit a low grain boundary resistance such that the total conductivity is due almost exclusively to the volume conductivity.

Another advantage of the materials is their high chemical stability. The materials exhibit in particular no detectable changes when heated in contact with melted lithium. At temperatures of up to 350°C and direct voltages of up to 6 V there is no chemical decomposition.

According to another aspect the present invention concerns processes for producing the solid ion conductors having a garnet-like structure. The compounds can be formed by reacting appropriate salts and/or oxides of the elements that are contained therein for example by means of a solid phase reaction. Particularly suitable starting materials are nitrates, carbonates and hydroxides which during the course of the conversion are converted into the corresponding oxides.

In particular the present invention concerns processes for producing solid ion conductors of the composition $L_{5+x}A_xG_{3-x}M_2O_{12}$ (e.g. $Li_6ALa_2M_2O_{12}$). The materials can be obtained by reacting appropriate salts and/or oxides of A, G and M with a hydroxide, nitrate or carbonate of L in a solid phase reaction. In this case A and M are defined as above. The divalent metal A is preferably used in the form of nitrates. In this connection $Ca(NO_3)_2$, $Sr(NO_3)_2$ and $Ba(NO_3)_2$ are preferred. La is preferably used for G, which is preferably used in the form of La_2O_3. M is advantageously used as an oxide and Nb_2O_5 and Ta_2O_5 are preferred. L is preferably used in the form of LOH, LNO_3 or L_2CO_3. For example $LiOH{\cdot}H_2O$ can be preferably used. In order to compensate a weight loss of L (e.g. L = Li) during the heat treatment of the samples, the corresponding salt is preferably used in an excess; an excess of 10 % is for example suitable.

The starting materials are mixed in a first step and can for example be ground by zirconium oxide ball-milling in 2-propanol. The mixture obtained in this manner is subsequently heated for several hours, preferably for 2-10 h in air at temperatures in the range of preferably 400 – 1000°C. Temperatures of ca. 700°C and a heat treatment period of about 6 hours are particularly suitable for this. A grinding process is subsequently again carried out, preferably also by zirconium oxide ball-milling in 2-propanol. The reaction product is subsequently pressed at isostatic pressure into moulded pieces, for example into pellets. These are then preferably sintered for several hours, preferably for 10-50 h, more preferably for 20-30 h at

temperatures in a range of preferably 700-1200°C, more preferably 800-1000°C. Temperatures of about 900°C and a heat treatment period of about 24 hours are particularly suitable for this. In this sintering process it is advantageous to cover the samples with a powder of the same composition in order to avoid excessive losses of the L-hydroxide.

The solid ion conductors (e.g. lithium conductors) obtained by the production process of the present invention are a valuable starting material as solid electrolytes.

Since the materials have an unusually high ion conductivity while having a negligible electron conduction, they can be used as a solid electrolyte for batteries (e.g. lithium batteries) with a very high energy density. As a result of the high resistance of the materials towards chemical reactions e.g. with elemental lithium and towards conventional electrode materials, the solid lithium ion conductors of the present invention can for example be used practically in lithium ion batteries.

The resistance of the phase boundary between the solid electrolyte of the present invention and the electrodes is also very small compared to common electrolyte materials. As a result batteries can be produced using the materials according to the invention which have a relatively high power (high currents). The use of the solid-state electrolytes of the present invention improves safety compared to the use of liquid electrolytes. This is particularly advantageous for an application in motor vehicles.

Another aspect of the present invention concerns the use of the solid ion conductors (e.g. lithium ion conductors) in electrochromic systems (windows, screens, facades etc.) as well as for instantaneous energy storage or release in super-capacitors (supercaps). In this connection energy densities of capacitors of 100 F/cm^3 can be achieved by using the ion conductors according to the invention. Another aspect of

the invention is the use of the garnet-like solid ion conductors as sensors for example for numerous gases.

The solid ion conductors of the present invention can be used in the form of pellets, or as thin layers in a crystalline or amorphous form.

Figures:

Fig. 1 shows a unit cell of the crystal structure of $Li_5La_3M_2O_{12}$ (M=Nb, Ta);

Fig. 2 shows the measured conductivity of $Li_6BaLa_2Ta_2O_{12}$ in comparison with other solid lithium ion conductors. The materials according to the invention have very high ionic conductivities that are comparable with those of $Li_{3,5}P_{0,5}Si_{0,5}O_4$ or even Li_3N.

Fig. 3 shows the equilibrium electron current as a function of the applied voltage for $Li_6BaLa_2Ta_2O_{12}$ obtained at 22°C and at 44°C by Hebb-Wagner (HW) measurements with a lithium ion blocking electrode using lithium as a reference electrode. The measurements were carried out in a glovebox filled with argon at an oxygen partial pressure of < 1 ppm.

The present invention is further illustrated by the following example.

Example: Production of pellets of $Li_6ALa_2Ta_2O_{12}$ (A = Ca, Sr, Ba)

La_2O_3 (predried at 900°C for 24 h), Nb_2O_5 and $A(NO_3)_2$ were mixed in a stoichiometric ratio with a 10 % excess of $LiOH{\cdot}H_2O$ and ground for 12 h in 2-propanol using zirconium balls. The mixture obtained was heated for 12 h in air to 700°C and subsequently again ground by balls. Subsequently the mixture was

pressed into pellets at isostatic pressure and covered with a powder of the same composition to avoid excessive losses of the lithium oxide. The pellets were sintered for 24 h at 900°C. Subsequently the conductivity and the chemical stability of the resulting solid lithium ion conductors was examined. The results are shown in table 1 and in figures 2 and 3.

Table 1: Resistance of $Li_6ALa_2Ta_2O_{12}$ (A = Sr, Ba) at 22°C in air

Compound	R_{vol} [kΩ]	C_{vol} [F]	R_{gb} [kΩ]	C_{gb} [F]	C_{el} [F]	σ_{total} [Scm^{-1}]	E_a [eV]
$Li_6SrLa_2Ta_2O_{12}$	18.83	$3.0x10^{-11}$	3.68	$8.5x10^{-9}$	$5.7x10^{-6}$	$7.0x10^{-6}$	0.50
$Li_6BaLa_2Ta_2O_{12}$	3.45	$1.2x10^{-11}$	1.34	$1.3x10^{-7}$	$1.2x10^{-6}$	$4.0x10^{-5}$	0.40

vol: volume
gb: grain boundaries

Claims

1. Solid ion conductor, characterized in that it has a garnet-like crystal structure and that it has a higher ion conductivity than $3.4x10^{-6}$ S/cm.

2. Solid ion conductor, characterized in that it has a garnet-like crystal structure and that it has a stoichiometric composition which is formally derived by aliovalent substitution of $Li_5La_3M_2O_{12}$ in which M is Nb or Ta.

3. Solid ion conductor, characterized in that it has a garnet-like crystal structure and that it has a stoichiometric composition $L_{5+x}A_yG_zM_2O_{12}$, wherein
L is in each case independently an arbitrary preferably monovalent cation,
A is in each case independently a monovalent, divalent, trivalent or tetravalent cation,
G is in each case independently a monovalent, divalent, trivalent or tetravalent cation
M is in each case independently a trivalent, tetravalent or pentavalent cation,
$0 < x \leq 2$, $0 \leq y \leq 3$, $0 \leq z \leq 3$ and
wherein O can be partially or completely replaced by divalent and/or trivalent anions such as e.g. N^{3-}.

4. Solid ion conductor as claimed in any of the previous claims, wherein the stoichiometric composition is

$$L_{5+x}A_xG_{3-x}M_2O_{12}$$

and wherein
$0 < x \leq 1$,
L is a monovalent alkali metal cation,
A is a divalent metal cation,

G is a trivalent cation and

M is a pentavalent cation.

5. Solid ion conductor as claimed in claim 3 or 4, wherein L is selected from Li, Na and K can in each case be the same or different.

6. Solid ion conductor as claimed in claim 5, wherein L is Li.

7. Solid ion conductor as claimed in one of the claims 3 to 6, wherein A is selected from divalent cations preferably alkaline earth metal ions.

8. Solid ion conductor as claimed in any of claims 3 to 7, wherein M is selected from transition metal ions.

9. Solid ion conductor as claimed in any of claims 3 to 8, wherein A is selected from Ca, Sr and/or Ba and wherein M is selected from Nb and Ta.

10. Solid ion conductor as claimed in claim 8 or 9, wherein A is selected from Sr and Ba and wherein M is Ta.

11. Solid ion conductor as claimed in any of claims 3 to 10, characterized in that it is stable towards elemental lithium at lithium activities corresponding to a voltage of 5 V.

12. Process for producing a solid ion conductor as claimed in one of the previous claims, characterized in that salts and/or oxides of L, A, G and M are reacted together.

13. Process as claimed in claim 12, characterized in that the reaction takes place in a solid phase reaction.

14. Process as claimed in any of claims 12 or 13 for the production of a solid ion conductor as claimed in claim 4, characterized in that L and A are used in the form of nitrates, carbonates or hydroxides and are reacted with G_2O_3 and M_2O_5.

15. Process as claimed in any of claims 12 to 14, which comprises the following steps:
(a) mixing the starting materials and ball-milling, preferably using zirconium oxide balls in 2-propanol,
(b) heating the mixture from (a) in air for 2-10 h to 400-1000°C;
(c) ball-milling, preferably using zirconium balls in 2-propanol;
(d) pressing the mixture with isostatic pressure into pellets; and
(e) sintering the pellets covered with a powder of the same composition for 10-50 h at 700-1200°C.

16. Process as claimed in claim 15, wherein
in step (b) the mixture is heated for 6 h to 700°C; and
in step (e) the pellets are sintered for 24 h at 900°C.

17. Use of a solid ion conductor as claimed in any of claims 1 to 11 in batteries, accumulators, supercaps, fuel cells, sensors and/or electrochromic devices such as windows, screens and facades.

18. Use as claimed in claim 18, wherein the solid ion conductor is used in the form of pellets, as a thin layer, in a crystalline or amorphous form.

Abstract

The present invention concerns chemically stable solid lithium ion conductors, processes for their production and their use in batteries, accumulators, supercaps and electrochromic devices.

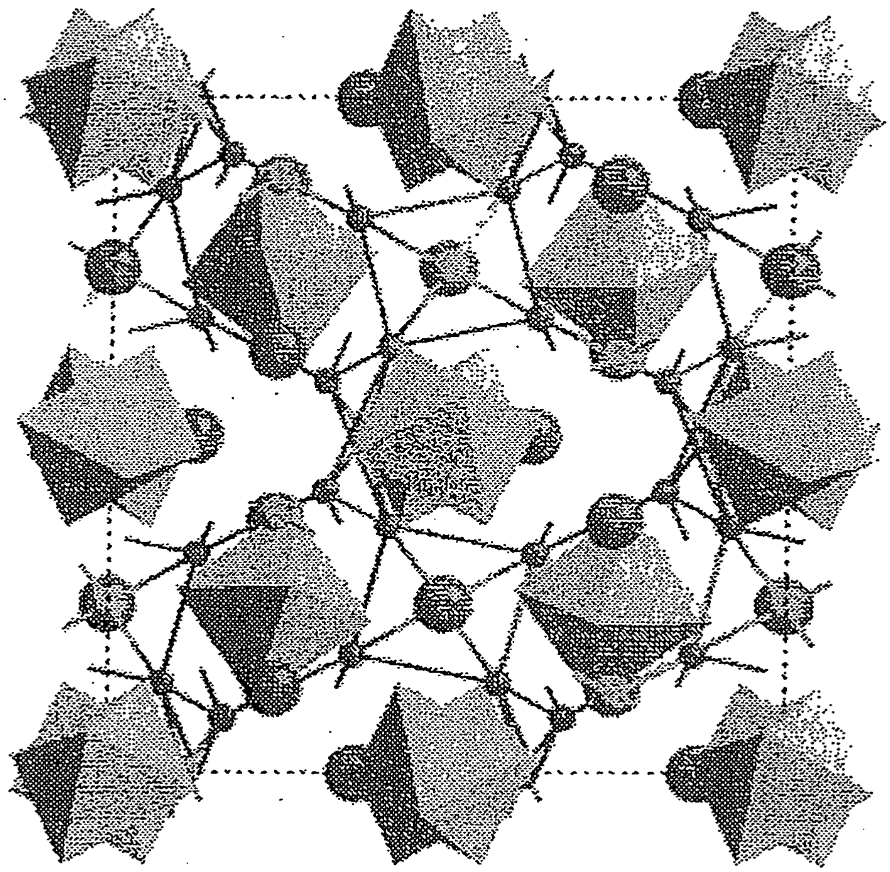
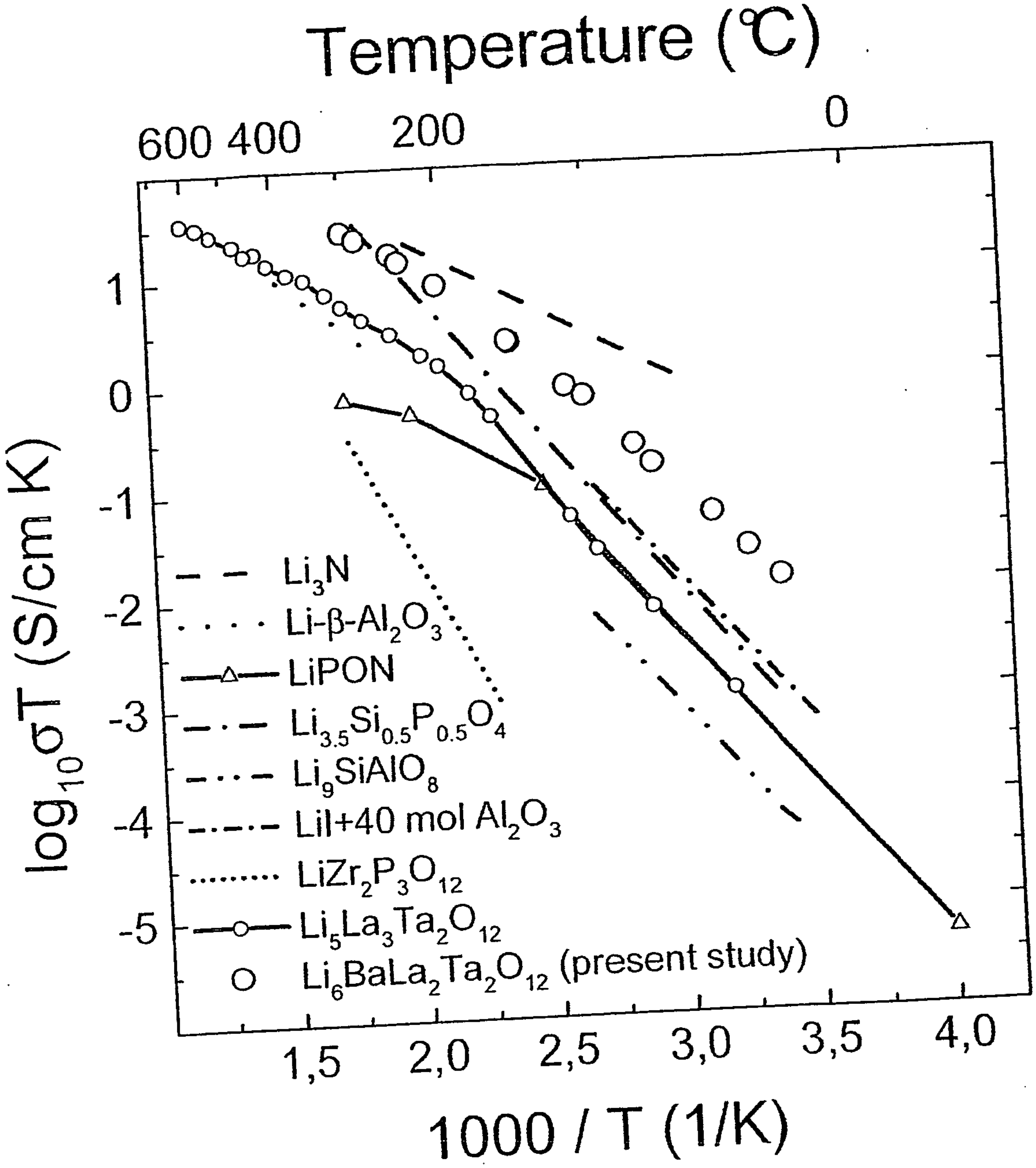
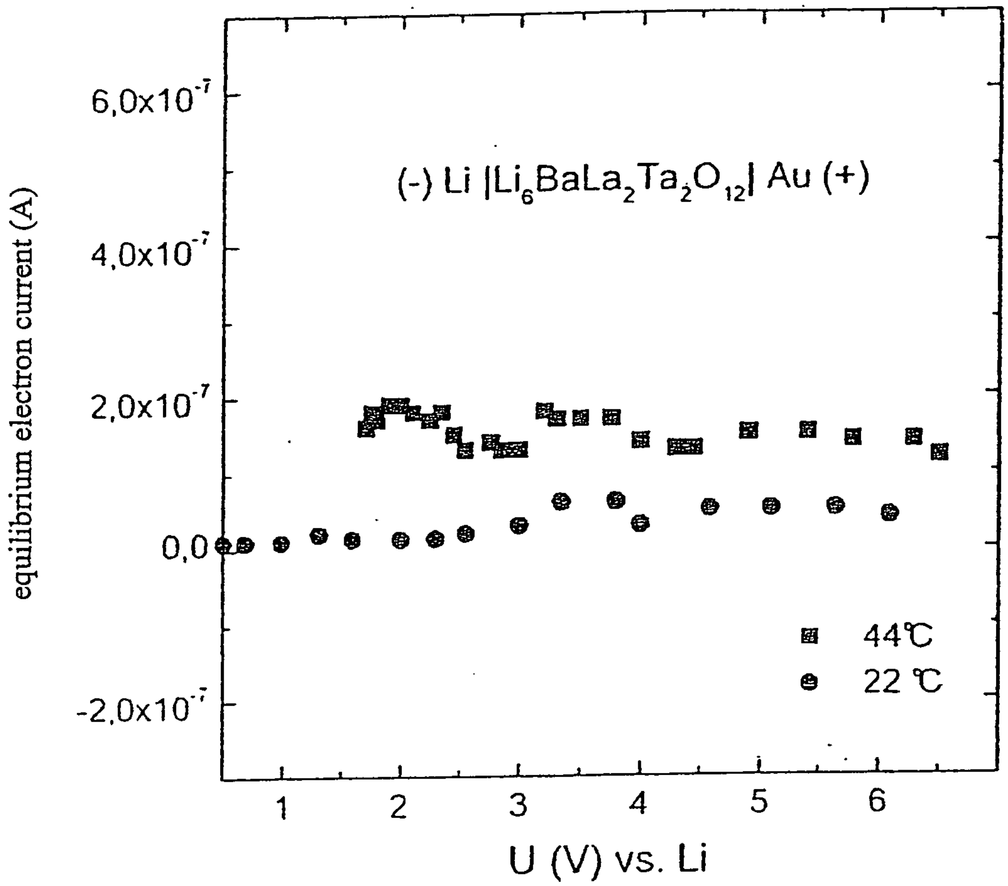


Fig. 1



Temperature (℃)
600 400
200
0
1
0
-1
-2
-3
-4
-5
$\log_{10}\sigma T$ (S/cm K)
Li_3N
$Li\text{-}\beta\text{-}Al_2O_3$
LiPON
$Li_{3.5}Si_{0.5}P_{0.5}O_4$
Li_9SiAlO_8
LiI+40 mol Al_2O_3
$LiZr_2P_3O_{12}$
$Li_5La_3Ta_2O_{12}$
$Li_6BaLa_2Ta_2O_{12}$ (present study)
1,5
2,0
2,5
3,0
3,5
4,0
1000 / T (1/K)

Fig. 2



6,0x10⁻⁷
4,0x10⁻⁷
2,0x10⁻⁷
0,0
-2,0x10⁻⁷
equilibrium electron current (A)
(-) Li |$Li_6BaLa_2Ta_2O_{12}$| Au (+)
44℃
22 ℃
1
2
3
4
5
6
U (V) vs. Li

Fig. 3